

TECHNICAL NOTE

D-920

STABILITY AND CONTROL CHARACTERISTICS OF A
SMALL-SCALE MODEL OF AN AERIAL VEHICLE
SUPPORTED BY TWO DUCTED FANS

By Lysle P. Parlett

Langley Research Center
Langley Field, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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SUMMARY

An investigation has been made to determine the stability and control characteristics in hovering and in forward flight of a free-flight model representing a type of vertical-take-off-and-landing aircraft which utilizes two fixed ducted fans as its sole source of lift and propulsion. The model, having fans 28 inches in diameter, was considered to be approximately one-third the size of a full-scale aircraft. Control moments for most of the hovering tests and all the forward-flight tests were provided by remotely controlled compressed-air jets at the sides and ends of the model. For one brief phase of the hovering investigation a system of vanes in the duct slipstreams was substituted for the jets as a means of roll control. During the forward-flight tests, the model was flown with both the tandem and side-by-side duct arrangements.

In hovering the model exhibited strongly divergent oscillations about the pitch and roll axes. The pitching oscillation of the tandem configuration was of a fairly long period and was not particularly difficult to control; the rolling oscillation, however, was of a relatively short period and was extremely difficult to control. Both oscillations could be completely eliminated by the addition of a sufficient amount of artificial damping. The control moments produced by the vane-type roll control system were weak and were accompanied by a side force of appreciable magnitude and undesirable direction.

In forward flight the model required an undesirably large nose-down tilt angle for equilibrium at any appreciable speed. A vane was placed transversely in the slipstream of the forward duct of the tandem configuration in an attempt to reduce this tilt angle. The vane was effective in reducing the tilt angle but apparently caused an increase in the power requirements and in the angle-of-attack instability. Without the vane, a forward speed of 30 knots (full scale) required a nose-down tilt angle of about 30° . A powerful pitch control moment was required not only to maintain the trim attitude but also to

overcome the effects of instability with angle of attack. Less pitch control moment was required for the tandem configuration than for the side-by-side configuration at any given forward speed.

The instability in roll increased with forward speed. No forward speeds in excess of about 20 knots (full scale) were achieved until the artificial damping in roll and the yaw control moment were increased appreciably above values which had proved satisfactory for hovering flight.

INTRODUCTION

There has been much interest in the development of a simple, inexpensive, easily operated vertical-take-off-and-landing (VTOL) vehicle for aerial reconnaissance and light transport missions. Some of the operating characteristics desired for the vehicle include hovering capability, forward speeds up to about 50 knots, and a payload of 1,000 pounds. The opinion appears to be widely shared that a vehicle having the desired characteristics would be one incorporating some arrangement of multiple ducted fans as the main source of lift and propulsion. Although some information has been available on the basic characteristics of ducted fans, the areas of application in which ducted fans might be utilized in groups have until recently remained largely unexplored. To provide information on the stability and control characteristics of multiple-duct vehicles, the National Aeronautics and Space Administration has undertaken a program of force tests and free-flight tests on small-scale models generally representative of a number of configurations suggested by manufacturers. This paper presents the results of a series of free-flight tests made to determine the stability and control characteristics in hovering and in forward flight of a model representing a type of VTOL aircraft which utilizes two fixed ducted fans as its sole source of lift and propulsion. Reference 1 presents a discussion, based in part on results of some of these tests, of certain stability and control problems to be anticipated with a vehicle depending upon fixed ducted fans for its lift and propulsion.

APPARATUS AND TESTS

Model

The model, shown in figures 1 to 4, was not meant to represent any particular full-scale machine; rather, it was intended to be simply a

research vehicle (of approximately one-third scale) which might yield information generally applicable to a number of two-duct configurations.

The ducts, of sheet aluminum construction, were located at each end of a simple wooden body. Near the exit of each duct was a fan which had four 3-inch-chord wooden blades. These blades were set to an angle, measured at the 0.75-radius station, of 18° to the plane of rotation. Clearance between blade tip and duct wall was about $1/8$ inch. Power was supplied to the fans by two pneumatic motors, one located in each duct. These motors were driven by a common source of compressed air but were not otherwise interconnected.

For most of the tests, the model control moments were furnished by small air jets located at the sides and ends of the model. Some of these jet-reaction controls were operated by pilots who controlled them remotely through the flicker-type (full on or off) electropneumatic actuators used on all models by the Langley VTOL Section. The actuators were equipped with integrating-type trimmers which trimmed the control a small amount in the direction the control was moved each time a control deflection was applied. With actuators of this type, a model becomes accurately trimmed after flying a short time in a given flight condition. For the tandem configuration, the remotely controlled jets used in the hovering tests provided moments of about ± 22 foot-pounds in pitch, ± 9 foot-pounds in roll, and ± 11 foot-pounds in yaw.

Other jet controls were employed at times to produce artificial damping for the model. In this application, the jet controls were driven by pneumatic actuators which moved in response to signals from gyroscopic devices sensitive to angular velocities. The system was set up so that a control moment could be produced automatically about any given axis, which would be proportional to the angular velocity about that axis and in the direction to reduce the velocity and would thereby add damping to the model motions.

For one particular set of hovering tests with the tandem model, all roll control moments were provided not by the air jets but by a system of vanes placed in the slipstream of the ducts. Details of these vanes are shown in figure 2.

During one brief phase of the forward-flight tests, a single fixed vane was installed along a transverse diameter of the slipstream from the forward duct in the tandem configuration. (See fig. 3.) This vane was not a control surface but was merely intended to provide a forward force to help control the model in forward flight.

The mass characteristics of the model varied slightly from one phase of testing to another, as control mechanisms, vanes, ballast

weights, and so forth, were added or removed, but the following values are believed to be reasonably representative of average values for the model with the tandem arrangement:

Weight, lb	80
Moment of inertia about long horizontal axis, slug-ft ²	2.2
Moment of inertia about short horizontal axis, slug-ft ²	9.6
Moment of inertia about vertical axis, slug-ft ²	12.5

Hovering Setup and Procedure

The hovering tests were performed in a large, completely enclosed area which provided protection from random disturbances due to wind. Some slight recirculation developed in this area during flights, but this did not seem to have any appreciable effects on the model performance.

The model was equipped with a steel safety cable, by means of which crashes could be averted in the event that control over the model was lost. This cable ran from an attachment point just above the model center of gravity through a pulley fixed to the building structure about 40 feet above the floor, then down to a safety cable operator stationed on the floor. A flight cable, made up of light electric cables and flexible plastic tubes, was used to conduct remote-control signals and compressed air to the model during flight. The flight cable was attached to the model near the center of gravity and was fastened along the steel safety cable and ran approximately horizontally out to the supply connections for the electrical signals and compressed air.

The electrical control signals originated at control boxes which were operated by pilots stationed on the floor of the flight area. Although it is in some cases possible for one man to operate all three controls successfully, the usual test technique is to assign separate pilots to the roll, pitch, and yaw controls. Through this division of pilot duties, each man is able to study in detail that particular phase of the model's behavior with which he is directly concerned. A fourth man operated a throttle valve which controlled the supply of compressed air to the fan motors in such a manner as to maintain approximately the desired altitude for flight.

The general procedure for the hovering tests is best illustrated by the description of a typical flight. Tests usually began with the model supported in the air by the safety cable. The power operator then opened the throttle valve, the three pilots manipulated their respective controls, and the safety cable operator adjusted the cable length until the model attained a trimmed hovering condition, with the

safety cable slack, at an altitude of about 15 feet above the floor. Then, certain experiments with the controls were performed, depending upon the nature of the investigation, and the response of the model was noted. Normally, the motions about only one axis at a time were subject to experimentation; motions about the other two axes were restricted to a minimum by the efforts of the two pilots having direct control about those axes. In some cases, artificial stabilization was employed to aid in further minimizing these extraneous motions. At the conclusion of a flight, power was reduced and the weight of the model was again taken by the safety cable. During the take-off-and-landing tests, the model started from a condition of rest on the floor. Power was applied until the model had risen to an altitude of about 10 or 15 feet. After a brief period of steady hovering flight the power was adjusted for descent and was cut off abruptly as the model touched the floor.

Forward-Flight Setup and Procedure

The forward-flight tests were performed in the test section of the Langley full-scale tunnel. A drawing of the setup for these tests is presented as figure 5. The model and the method of controlling it were the same as for the hovering tests.

The forward-flight tests usually started with the model hovering in still air in the test section of the tunnel. After a trim condition had been attained in hovering, the tunnel was started and the airspeed was increased slowly. As the airspeed increased, the pitch pilot applied nose-down control to tilt the model to the attitude required for equilibrium. All flights began and ended with the model supported by the safety cable. Some of the tests, made to explore the flight characteristics at some particular speed, began with the tunnel preset to a given airspeed. Model power and tilt angle were then adjusted to the values required for trim. These values and the tunnel speed were then held constant for a flight usually of several minutes duration.

RESULTS AND DISCUSSION

In attempting to interpret the results of free-flight model tests, one must bear in mind that the behavior of a model remotely controlled by human pilots is not necessarily an exact representation of the behavior of a full-scale machine. Certain scale effects exist which usually cause the model tests to yield results which appear somewhat pessimistic when compared with actual flight results. Among these effects, and of particular importance to the tests discussed in this paper, is the time lag between the requirement for a control and its actual application. In contrast to the pilot of a full-scale machine,

who can sense accelerations kinesthetically and apply corrective controls without waiting for a displacement to develop, the model pilot usually applies controls only in response to an observed displacement. This introduces a time lag into the model pilot's response, and, when it is considered that model angular motions are inherently more rapid than those of a full-scale machine, it is seen that the phase lag between the need for a control and its actual application may be appreciably larger for the model than for the full-scale machine and that the model may fly somewhat less smoothly than the full-scale machine.

Hovering Flight

For purposes of discussion of the hovering phase of the investigation, the model is considered to be representative of a tandem two-duct machine - that is, motions about the long horizontal axis are considered rolling motions and motions about the short horizontal axis are considered pitching motions.

Longitudinal stability characteristics.- Possibly the most outstanding dynamic stability characteristics of the model in hovering flight were the strongly unstable oscillations in both pitch and roll. Graphic representation of a typical uncontrolled pitch oscillation, obtained from motion-picture records of model flights, is presented as figure 6. These oscillations, which have a powerful effect on the flight behavior, seem inherent in most ducted-fan configurations since the source of the exciting force appears to lie in the response of the aerodynamic forces on the duct and fan to changes in translational velocities. Quantitative data on these force variations, obtained in a series of force tests on this model, are presented in reference 2. If the force-test information is correlated with the observed flight behavior, the following qualitative analysis of the mechanics of an oscillation may be obtained.

For purposes of illustration, an oscillation in pitch is considered although the general argument may apply equally well to an oscillation in roll. If the model, initially in a trimmed hovering condition, encounters some disturbance which produces an angular displacement about the pitch axis, the resultant thrust vector is displaced from the vertical to some new attitude in which it has a horizontal component in the direction toward which the model was pitched. If the initial pitch displacement is considered to be in the nose-down direction, the model is then accelerated forward. As the forward velocity increases, aerodynamic forces develop which produce a nose-up pitching moment in the direction to restore hovering equilibrium. The relationship between the aerodynamic forces, their variations with pitch angle, pitching velocity, and forward velocity, and the mass characteristics of the model, however,

are such that the model acquires a nose-up pitching velocity, overshoots the level attitude required for hovering equilibrium, and decelerates to zero forward velocity, by which time the angular displacement in the nose-up direction has become of even greater magnitude than was the initial nose-down angular displacement. The longitudinal forces are then heavily out of balance toward the rear, and the model enters the second half-cycle of a rapidly divergent oscillation.

Notwithstanding the presence of a divergent pitching oscillation, the model was not particularly difficult to fly in pitch. An important reason for this was that the period of the oscillation was approximately $3\frac{1}{2}$ seconds, which was long enough, compared with the pilot's reaction time, to allow the pilot time to apply a corrective control in the proper phase to arrest the oscillation before any appreciable amplitudes developed. A second reason for the relative ease with which the model could be flown in pitch was the damping in pitch afforded by the tandem duct arrangement. A discussion of the effect of duct arrangement on damping is presented in reference 1. Another reason for the ease of control in pitch was the large control moment available to the pilot. This moment, produced by the jet-reaction system previously discussed, amounted to approximately 122 foot-pounds and afforded angular accelerations in pitch of approximately 2.3 radians per second per second. This moment proved to be powerful enough to arrest the oscillation even after it had intentionally been allowed to develop an appreciable amplitude.

When artificial damping equal to or in excess of approximately 3.5 foot-pounds per degree per second of pitching velocity was added, the model became completely stable in pitch and would fly for long periods of time without the need for manual pitch control other than an occasional trim correction required to restrain a random wandering tendency. It is felt that this wandering was due to such causes as recirculation of the slipstream in the test area or to slight differential changes in the thrust of the model fans.

Lateral stability characteristics.- The oscillation in roll presented a much more serious control problem than did the oscillation in pitch. The effects of the aerodynamic forces and the mass characteristics of the basic model combined to produce an oscillation of so short a period compared with the pilot's reaction time that the roll pilot had great difficulty in applying control in the proper phase to arrest the oscillation. The violent instability of the rolling oscillation prohibited the measurement of the period to the same degree of accuracy achieved in the longitudinal stability investigation. Analysis of the best available data indicates, however, that a value of approximately 2 seconds may reasonably be assigned to the period of the rolling oscillation. The jet-reaction roll control moments of

approximately ± 9 foot-pounds resulted in angular accelerations in roll of approximately 4.2 radians per second per second. This roll control moment appeared adequate when applied in proper phase and before large amplitudes had developed. Although the magnitude of this control moment seemed to the roll pilot to be about the optimum, the extreme instability of the oscillation made flights very rough. So great were the demands imposed on pilot technique by the model that the duration of the flights was limited to about 2 minutes by physical fatigue of the roll pilot.

The addition of artificial damping to the model control system resulted in greatly improved flight characteristics. A damping rate of approximately 0.2 foot-pounds per degree per second of rolling velocity was found to be sufficient to produce a condition of neutral stability. When the damping rate was increased only slightly over this value, prolonged flights could be made with no need for a manual roll control other than an occasional trim correction required to restrain a random wandering tendency.

As pointed out previously, hovering tests were also made with a system of vanes located in the slipstream of the ducts, which was substituted for the jet control as a source of roll control moment. (See fig. 2.) Basically, the function of the vanes was to produce a moment by producing a force in the sidewise direction. The product of this force and its moment arm about the center of gravity was the roll control moment. Because the moment arm was rather short, due to the geometry of the model, relatively large forces were required to produce reasonable control moments. At each application of roll control, then, the model initially experienced an appreciable sidewise acceleration in the direction opposite to that in which it was intended to roll. A response of this nature is not only somewhat disconcerting to a pilot trying to control the position of an aircraft but also aggravates the stability problems in that a roll control given to arrest an oscillation produces a side force in the direction to reinforce the oscillation. The net result was that, although short flights (seldom longer than 20 seconds) were possible with the vane roll control, these flights were very rough, characterized by a great number of small abrupt lateral displacements, and demanded a high degree of pilot skill. A vane deflection of $\pm 28^\circ$ was the minimum which could produce adequate rolling moments.

The addition of a rate stabilization system to the control input to the vanes provided enough artificial damping to improve greatly the lateral stability characteristics of the model. A damping rate of 1.8° of vane deflection per degree per second of rolling angular velocity was the minimum required to counteract completely the unstable oscillatory tendency of the model. With this artificial damping, the model was fairly easy to control in roll and could be flown for long periods

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of time with only the occasional necessity for the application of manual roll control. The best flights obtained with this control system were, however, a little rough compared with the best flights obtainable with the jet control system.

Throughout the test program, the jet control was utilized as the source of yaw control. The model was neutrally stable about the yaw axis, so that most of the need for yaw control arose only from the necessity of counteracting the effects of slipstream recirculation and the changes in net torque due to random differential changes in fan rotational speed. A yaw control moment of ± 11 foot-pounds, producing angular accelerations in yaw of approximately 0.9 radian per second per second, proved to be quite satisfactory in hovering.

Take-offs and landings.- A series of take-offs and landings with the model remotely controlled about all three axes by means of jet-reaction controls, and with artificial damping in roll only, revealed no perceptible changes in the stability and control characteristics of the model as it passed through the ground-effect region. As might be expected, however, operation of the model near the ground was characterized by a lower power requirement. No actual power measurements were made, but an indication of the changes in power requirements was gained from noting the required changes in the setting of the throttle valve controlling power input to the model fan motors. Flights near the ground could be performed as easily as at higher altitudes. Indeed, some of the flights near the ground seemed even smoother because the vertical motions were minimized by the altitude stability afforded by the ground effect. It is possible that the ground effect may also have produced some attitude stability, which would have further contributed to smoothness of flight.

A few flights near the ground were attempted with the roll control vanes used for roll control and with the roll damper operating. These flights were somewhat rough, though not necessarily rougher than those at higher altitudes, and were limited in number because of the danger of damaging the model. Because vane deflections affect not only roll and side force but also total thrust, holding a given altitude, either in or out of ground effect, was more difficult than with the jet controls.

Forward Flight

Tandem arrangement.- Although the problems associated with this model in forward flight were primarily longitudinal ones, the flight behavior of the model in the initial stages of the forward-flight tests dictated that a solution to a lateral stability problem be effected before the longitudinal investigation could be extended to reasonably

high forward speeds. The particular lateral stability problem requiring solution was that of increasing dynamic instability with increasing forward speed. In the preceding discussion of the stability characteristics of the model in hovering flight, it is noted that the inherent lateral oscillation could be completely eliminated by the addition of a sufficient amount of artificial damping. At the outset of the forward-flight tests, however, it was found that values of artificial damping sufficient to produce lateral stability in hovering were not necessarily great enough to insure stability in forward flight. The increase in oscillatory instability with increasing speed has not been analyzed in detail, but it is evident that the model had all the major factors which are known to produce lateral oscillatory instability in an airplane. These factors are a high dihedral effect (large rolling moment due to sideslip), low or negative directional stability, high radii of gyration, and a nose-down inclination of the principal axis of inertia. With values of roll damping and yaw control sufficient for smooth stable flight in hovering, forward speeds of only about 20 knots (full scale) were attained before flights were terminated by the development of the unstable lateral oscillation. After the rate of artificial damping had been increased by approximately 70 percent and the yaw control moment increased from 11 to 22 foot-pounds, no further lateral stability problems were encountered. No measurements were made of the actual damping rate required for stability in forward flight.

After the speed limitations imposed by the lateral stability difficulties had been removed, flights were made during which a maximum speed of approximately 30 knots (full scale) was attained. In progressing from hovering flight to maximum forward speed, the nose-down control moment required for trim increased until at about 30 knots all the available nose-down control moment, augmented by a nose-down ballast moment of 7 foot-pounds, was being exerted. The nose-down tilt angle required for equilibrium at this speed was approximately 30° . In this condition, with no reserve control moment available, only a very slight disturbance was required to cause the model to nose up slightly. Because the model had an unstable variation of pitching moment with angle of attack, the nose-up pitching moment could then exceed the available nose-down control moment with the result that the model pitched up and drifted downwind in the tunnel test section.

Although the occurrence of a pitch-up at high speed invariably forced the termination of a test flight, the motion of the model during the pitch-up was not particularly violent. The forward tilt angle decreased, steadily but not very rapidly, while the increased drag accompanying the decreasing nose-down attitude caused the model to lose much of its forward speed. Because the tunnel speed remained essentially constant during the pitch-up, the model drifted downwind until its motion was arrested by the safety cable. Had the model been free to decelerate relative to the airstream, as would be the case in

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completely free flight out of doors, there are indications that the nose-up pitching moment would have decreased until it was less than the pitch control moment, at which time the pilot could have regained control of the model.

The angle-of-attack instability, reported in reference 2, which contributes heavily to the pitch-up was noted at all forward speeds, although it did not seriously impair the flight characteristics until the higher speeds were reached. This was due to the fact that the pitching moments developed were a function of the forward speed, whereas the maximum available pitch control moment was a constant value, independent of forward speed.

As has been mentioned in the section entitled "Apparatus and Tests," the model fans were driven individually by pneumatic motors having no mechanical interconnection. This arrangement gave rise to some difficulty in attaining a flight condition in which the model was completely trimmed in pitch. A series of static force tests, performed subsequent to the flight tests, indicated the changes in pitching moments which might result from random differential changes in fan speeds. Figure 7 shows the wide band of pitching moments required for trim through the forward-speed range covered during the flight tests. Because figure 7 presents data from only three tests through the speed range, it is reasonable to assume that an even wider band may have resulted from a greater number of tests. In any event, it may be seen that some of the longitudinal difficulties encountered in flight resulted from the nature of the model drive system.

As a means of increasing the nose-down control moment required for trim in forward flight, ballast weights were attached to the forward end of the model for some of the flights. The addition of these weights produced a forward shift in the center of gravity of as much as 10 percent of a duct diameter from the original position indicated in figure 1. With the forward center-of-gravity locations, the model was found to be easier to trim in forward flight, although no perceptible reduction of longitudinal instability was noted.

In an effort to reduce the forward tilt angle required for equilibrium at the higher forward speeds, a turning vane (fig. 3) was installed in the slipstream of the forward duct. It had originally been planned to use a cascade of vanes in each duct, but the downward force on the multiple-vane arrangements caused such a reduction in net lift that flights were impossible with the limited power available. With the single vane installed and deflected 15° the model attained a speed of approximately 28 knots (full scale) at a forward tilt angle of about 22° . Since the tilt angle at 28 knots for the basic model was nearly 30° , it can be said that the vane had some beneficial effect on the tilt angle. Its effect on power required was, however, apparently

quite detrimental. No actual measurements of power were made during the flight tests, but the setting required for the throttle valve for the pneumatic motors provided the basis for qualitative comparison. The turning vane had the additional undesirable effects of increasing the angle-of-attack instability and the nose-down control moment required for trim at any given forward speed. A more quantitative evaluation of the vane effect is presented by the force-test data of reference 2, although for the tests discussed in reference 2 the vane configuration was quite different from that of the flight-test model presently under discussion.

In spite of the trim, stability, and mechanical problems, the model with the tandem arrangement was not considered to be particularly difficult to fly in pitch. The motions were fairly slow, and, as long as the available pitch control moment appreciably exceeded the pitching moments developed by the fans and ducts, prolonged flights could be made consistently and easily.

Side-by-side arrangement.- Several flights were made with the model turned 90° about a vertical axis to produce a side-by-side arrangement of the ducts. The artificial damping system used about the roll axis in the tandem arrangement was retained as a pitch damper when the model was rotated to the side-by-side arrangement. Because it was known that the motions of the model in hovering were rapid and violent, no attempts were made to fly the side-by-side arrangement without artificial damping in pitch. No artificial damping was required in roll, however. It was the roll pilot's comment that the model was as easy to fly in roll in the side-by-side configuration without damping as in the tandem arrangement with artificial damping. It is possible, however, that lateral stability difficulties would have developed at speeds higher than those attained in the tests.

Ballast was added to produce a nose-down ballast moment of 7 foot-pounds. The early flights in this side-by-side arrangement resulted in uncontrollable pitch-ups at forward speeds of only about 5 knots. Two factors were apparently responsible for the pitch-ups occurring at a much lower speed than with the tandem arrangement: First, the nose-up pitching moment developed by the model was considerably larger for the side-by-side arrangement than for the tandem arrangement at any given forward speed. This effect is shown and discussed in reference 2. Second, the geometry of the model and the location and size of the control jets caused the pitch control moment to be reduced by more than one-half when the model was rotated to the side-by-side arrangement. When the pitch control effectiveness of the side-by-side arrangement was increased by mounting the pitch jet on a tail boom so that the maximum pitch control moment became approximately 85 percent of that available in the tandem arrangement, the pitch-up occurred at speeds of about 17 knots (full scale) which was approximately 60 percent of

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the maximum speed attained in the tandem arrangement. A graphical summary of the maximum speeds, with the corresponding nose-down tilt angles, for four model conditions is presented in figure 8.

CONCLUSIONS

On the basis of free-flight model tests of an aircraft supported by two ducted fans, the following conclusions are drawn:

1. The tendency exists toward the development of divergent oscillations about both the pitch and roll axes in hovering flight of a tandem duct arrangement. The pitching oscillation has a reasonably long period and is easy to control. The rolling oscillation, however, has a much shorter period and is extremely difficult to control.
2. The oscillations about either axis may be completely eliminated by the addition of sufficient artificial damping about the axes. The requirements for roll damping of the tandem configuration are increased as the model goes from hovering to forward flight.
3. The roll control characteristics produced by a system of control vanes installed in the slipstream of the duct of a tandem configuration and depending upon a side force to produce a control moment are unsatisfactory. Control moments are only marginal because of the small moment arm about the center of gravity, and the side force producing the control moment aggravates the rolling oscillation.
4. Undesirably large nose-down tilt angles are required for trim in forward flight for both the tandem and side-by-side arrangements. Slipstream vanes may provide some reduction in the tilt angle, but this reduction may be at the expense of increased longitudinal instability and higher power requirements.
5. The pitch control moment required for trim at a given forward speed is less for the tandem duct arrangement than for the side-by-side arrangement.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., May 9, 1961.

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2. Parlett, Lysle P.: Wind-Tunnel Investigation of a Small-Scale Model of an Aerial Vehicle Supported by Ducted Fans. NASA TN D-377, 1960.

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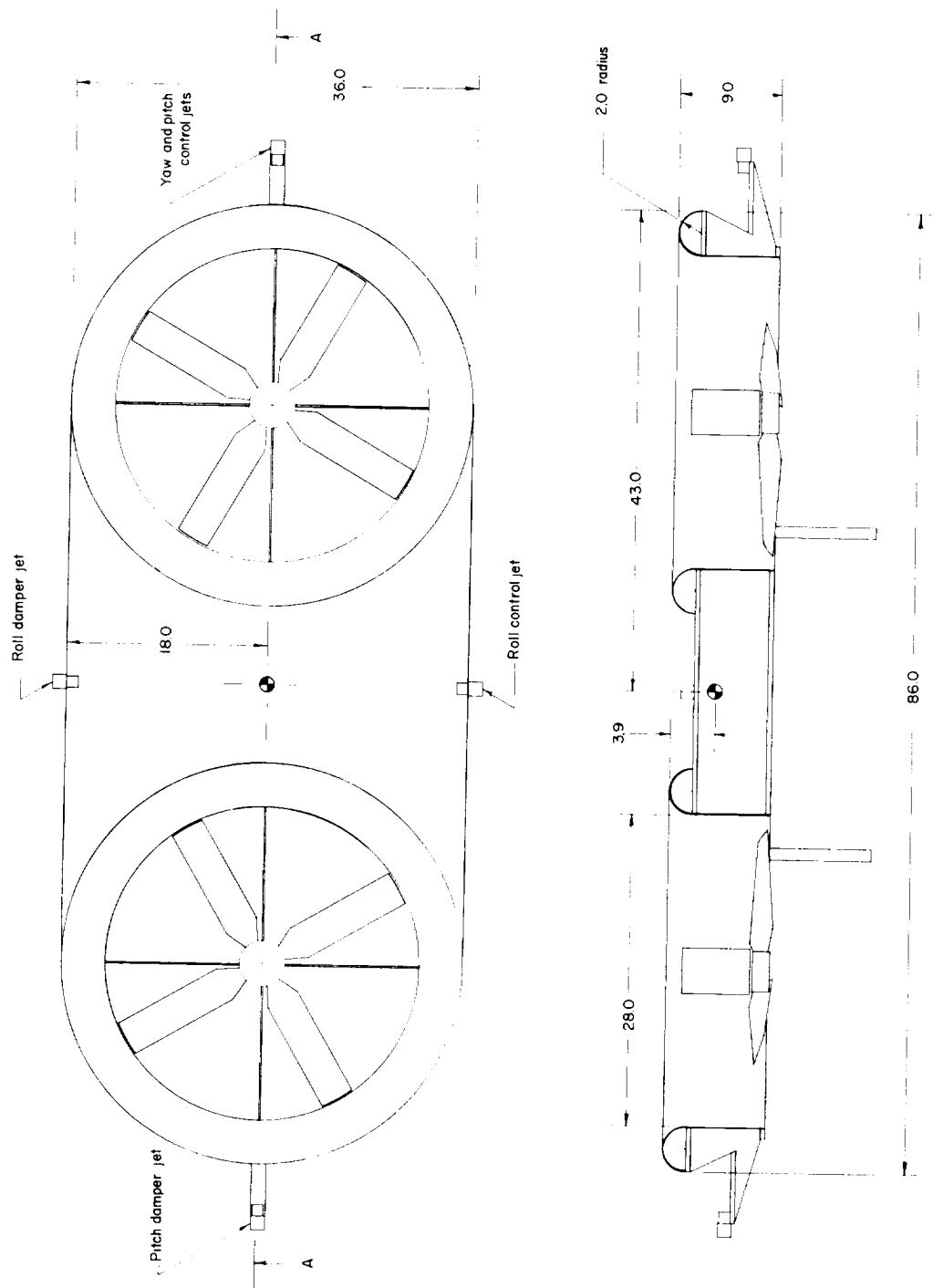


Figure 1.- Sketch of basic model. All dimensions are in inches.

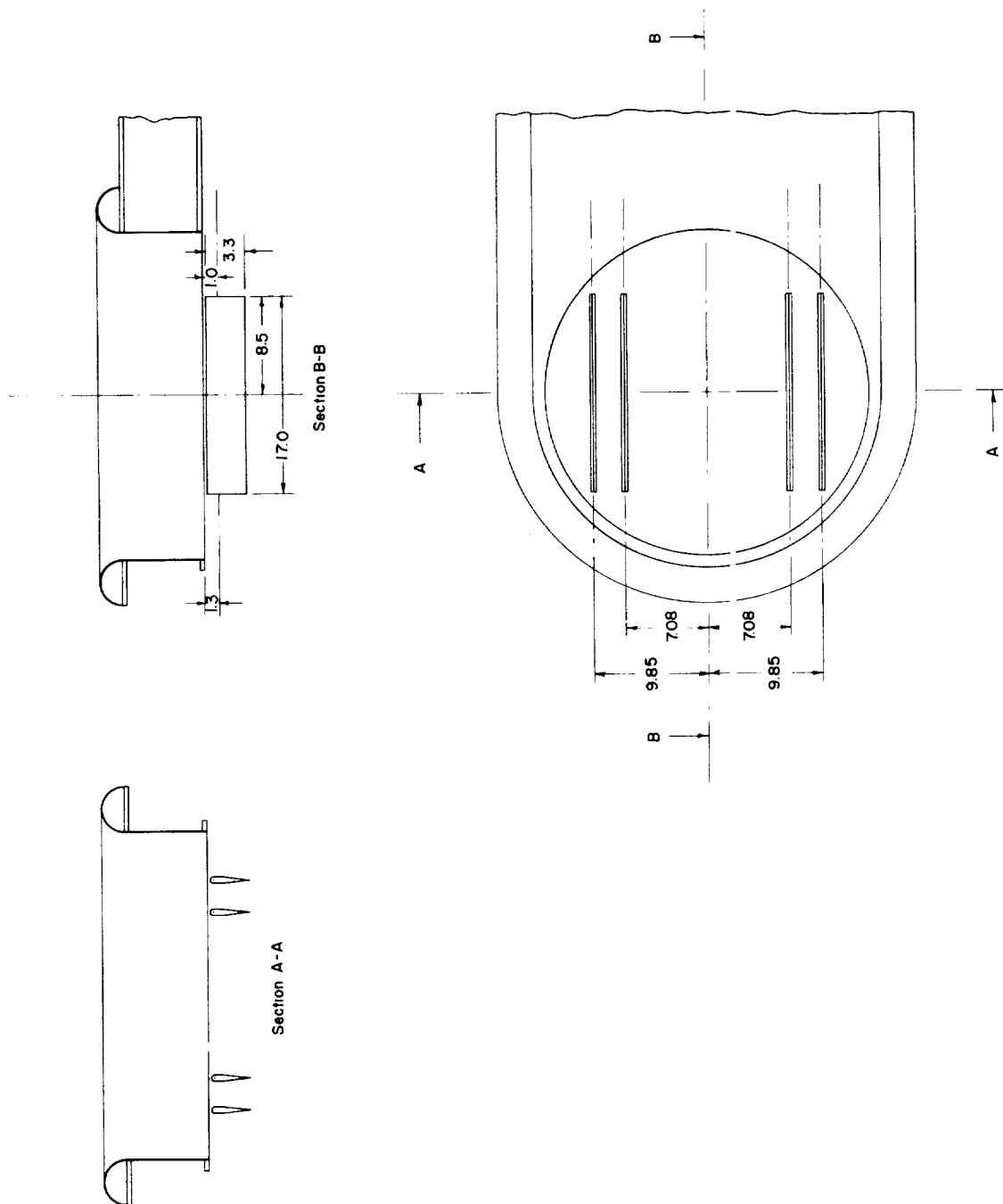


Figure 2.- Location and dimensions of vanes used in both ducts of tandem model for roll control in hovering flight. All dimensions are in inches.

Section A-A

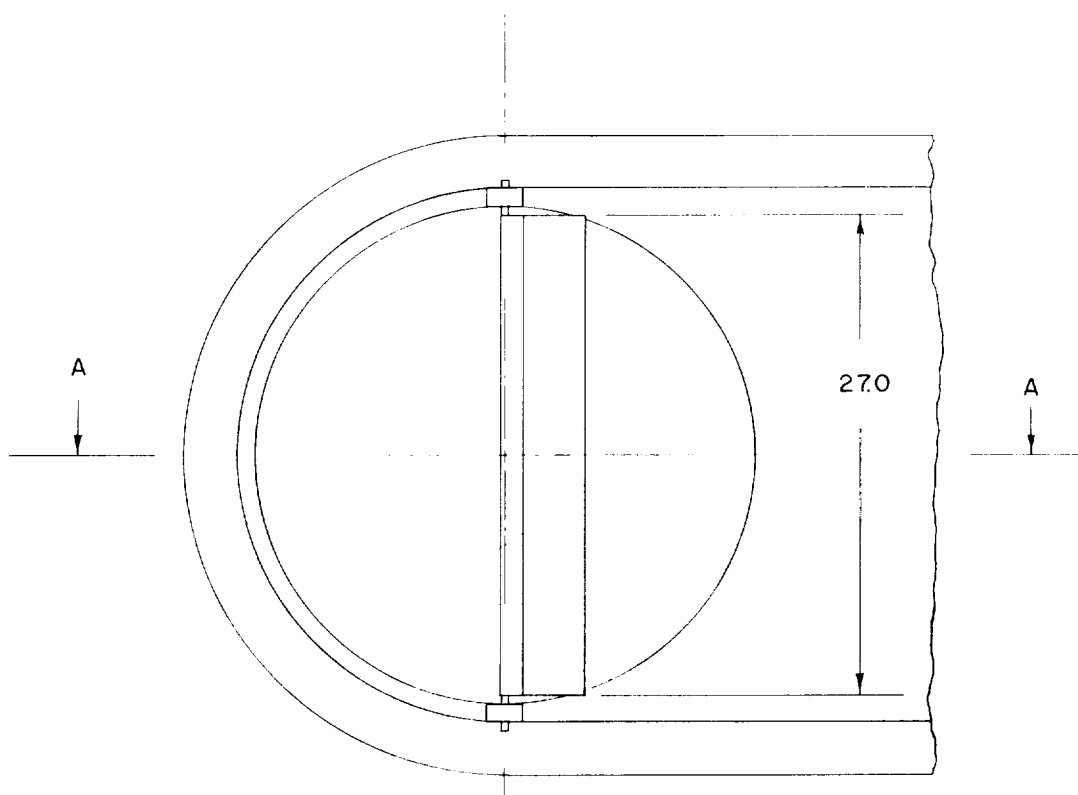
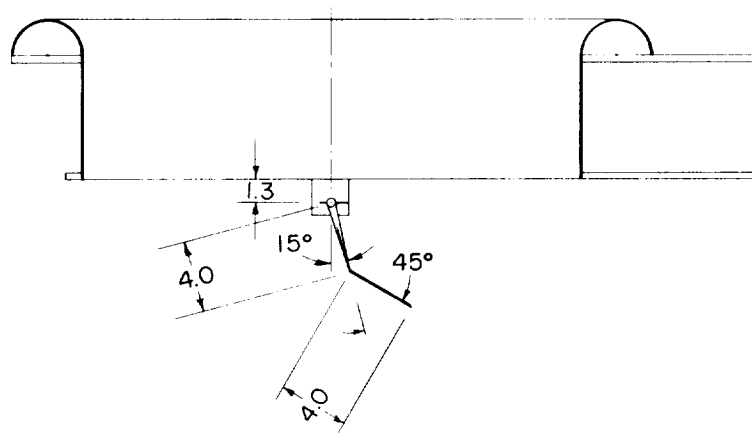


Figure 3.- Forward duct of tandem configuration, showing location and dimensions of vane used for pitch trim in forward flight. All linear dimensions are in inches.

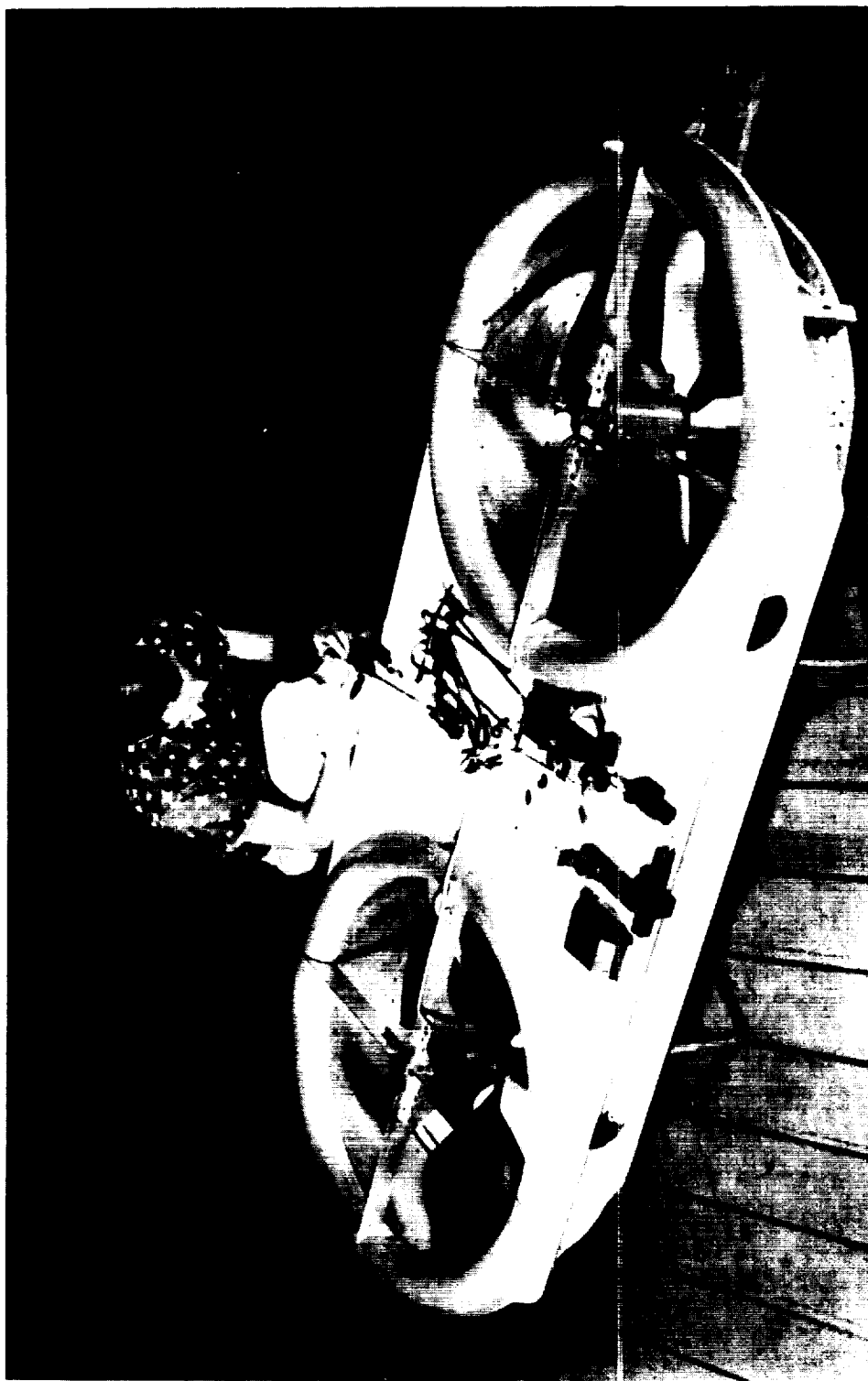


Figure 4.- Model used in the investigation.

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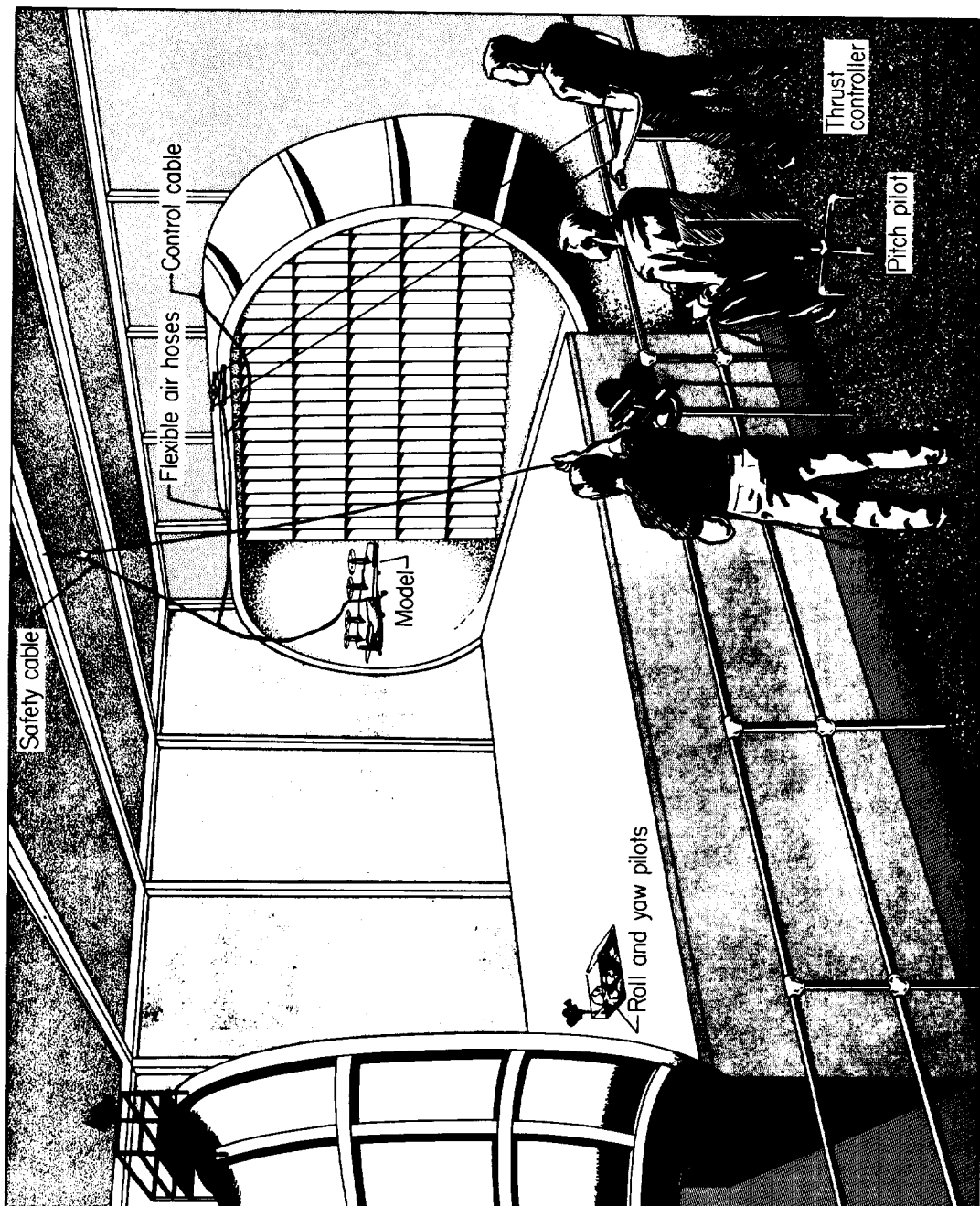


Figure 5.- Forward-flight test setup at the Langley full-scale tunnel.

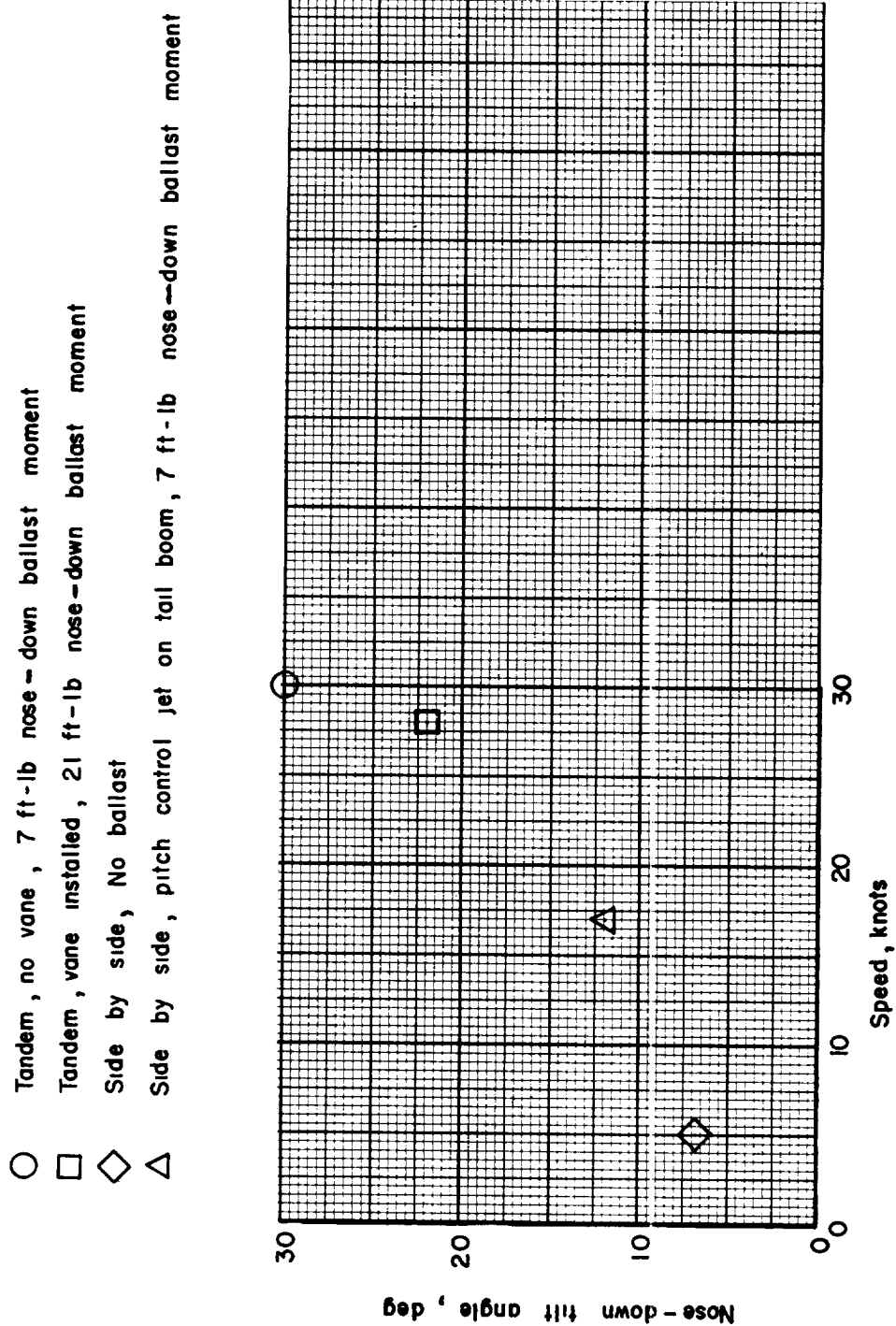


Figure 8.- Summary of maximum speeds (full scale) attained for four model conditions.

